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Offshore renewable energy in the Adriatic Sea with respect to the Croatian 2020 energy strategy

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ABSTRACT

July 1st 2013 Croatia joined the European Union (EU). During the acceding process the Croatian government strongly committed to an intensive development in the renewable energy sector. In particular, each EU member state is supposed to reach the mandatory 20% share of renewable sources in the total energy consumption by the year 2020, which goal now applies to Croatia as well. At this point, a significant Croatian renewable energy source is hydro power. However, it is at its peak and does not have a potential for further development due to limited natural hydro resources. On the other hand, onshore wind farms developed strongly in the past decade, with their limit in the sight though, as the most licenses for potential wind farm locations are already awarded by the Croatian government. At this point there is not a single offshore renewable energy power plant available in the Croatian part of the Adriatic Sea indicating an interesting possibility in that direction. Hence, in this study, we analyze a potential for development of an offshore renewable energy power plant in the Croatian part of the Adriatic Sea with likely implication on the environment and economy. We particularly focus on technology that would exploit the kinetic energy of wind and sea currents, whereas structural design issues, wind and tidal potential, sea depths, and sea traffic routes were thoroughly analyzed in order to identify the potential locations for the proposed renewable energy concepts. Electrical energy output is calculated and potential technical issues identified in order to highlight expected environmental and social benefits of such a challenging task as it is designing, manufacturing and maintaining of an offshore power plant in the Croatian part of the Adriatic Sea.

Contents

1. Introduction

Global reduction of fossil fuels reserves and increasing awareness on adverse effect of fossil fuel consumption on climate change significantly contributed to a strong development of

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renewable energy technology and application. Hence, leading world economies developed regulations and protocols in order to promote sustainable and renewable energy sources. In particular, EU became a worldwide pioneer in leading-edge application of renewable energy technology introducing the mandatory 20% share in renewable sources in the final energy consumption by the year 2020. As Croatia joined EU in the year 2013, its economy is now required to satisfy that agenda.

Namely, during negotiations for a full EU membership many challenging tasks were set in front of Croatia by signing the Stabilization and Association Agreement in 2001 and the Energy Community Treaty in 2005, whereas the requirements are particularly challenging in the energy sector. By those acts Croatia committed to take over and harmonize its legislative with the EU legislative in order to successfully integrate its energy sector into competitive EU energy market. Therefore, in 2007 Croatia signed the Kyoto protocol declaring itself in favor of a sustainable development by including a common responsibility for climate change and greenhouse gas emission reduction. Given those facts the Croatian Government set three basic objectives within its official Energy strategy, i.e. secure, competitive and sustainable energy sector within a flexible energy system consisting of various components and supply chains, [1,2]. Therefore, the Croatian energy sector is supposed to develop on efficient, green and cost-effective energy production with a particular focus on reducing energy imports and dependence on foreign supplies by diversification of energy sources, emphasizing the renewable energy sources.

In order to achieve those goals in accordance with the Directive on the promotion of the use of energy from renewable sources, [3] and the framework of the EU objectives defined in the Climate Action and Renewable Energy package for 2020, [4], reaching 20% share of renewable sources (including large hydro power plants), in the final energy consumption by 2020 became mandatory for Croatia, [2]. As in the year 2020 renewable energy will play key role in ensuring energy system sustainability and competitiveness, this fact motivated the European Commission to set a new and even more challenging goal of achieving at least 27% share of renewable sources of the EU's energy consumption by 2030, [4]. In order to achieve those objectives, Croatia needs to stimulate research, production, implementation, maintenance and decommission development of environmentally sustainable energy technologies by increasing investments in education and scientific research projects, while simultaneously encouraging the industry to gain the inevitable expertise and know-how skills of such a complex and multidisciplinary market sector. Following those principles, the renewable energy source structure in Croatia, foreseen for 2020 will consist of biomass (31.5%), hydropower (29.4%), wind energy (12.2%), biofuels (10.8%), solar energy (5.9%), biogas (3.1%), geothermal energy (1.3%) and other sources (5.8%), [1], where hydro- and wind power play quite an important role in achieving the 2020 targets. Therefore, it is crucial to thoroughly investigate possibilities in order to achieve the goals set.

According to data available in the Energy Strategy of the Republic of Croatia, [1], and the Statistical Energy Balance of the Republic of Croatia, [5], the total electrical energy consumption in Croatia in 2010 was 18.4 TWh (66.24 TJ), the production was 15.552 TWh (55.987 TJ), while the difference between them was covered through energy import. Electricity generation and consumption balance in Croatia for 2010 is shown in Fig. 1.

It can be noticed that large hydro - and wind power plants have about 41% share of the total produced electrical energy, almost solely due to hydro power, while final consumed electrical energy (industry, transport and general consumption including households, services, agriculture and construction) has significant 86% share of the total demand. It is estimated that the average annual growth of the final electricity consumption will be about 3.7% by 2020 resulting in final energy consumption of about 25.0 TWh (90 TJ), with similar share between final consumers. The growth will continue further on yielding 33.0 TWh (118.8 TJ) of final electricity demand in 2030, [1].

As expected, an increase in the total electricity demand by 2020 will be considerably larger than the increase of electricity generated in large hydro power plants. Therefore, the aim of maintaining the 2010 large hydro power plants and renewable energy sources share of 41% can be achieved solely by a significant increase of electrical energy generated by using renewable energy sources such as wind, biomass, solar, geothermal, waste or ocean power plants. Hence, it is expected that the total amount of installed wind turbine power by 2020 will reach the level of about 1200 MW, [1], while the rest of the required power can be supplied by solar or ocean power plans.

Currently, the only significant progress in renewable energy techniques application in Croatia is related to wind power plants. So far they have been built only onshore, particularly in the coastal area. Total wind turbine installed capacities for period between 2004 and 2011 is shown in Fig. 2.

It can be noticed that the wind power plants exhibited two significant development phases, i.e. between 2008 and 2009, and between 2010 and 2011. Currently, there are in total 12 wind power plants incorporating 132 onshore wind turbines with the total 225.25 MW of the installed wind power, [7].

In order to reach 1200 MW of installed power until 2020, an additional power of about 1000 MW needs to be provided. Such a demanding task can be accomplished by introducing new, inventive and state-of-the art offshore renewable energy plants as for example wind and tidal current power plants, which are discussed in more detail later in this study. In addition to required electrical energy production, Croatia has to ensure adequate transmission system of produced energy from energy source to the end user, as the power transmission proved to be a significant issue in designing the renewable energy power plants, [8]. In order to develop reliable and operable distribution network, as well as optimal conditions for expected development of electricity market, power lines between new power plants and consumers need to be provided along with increased transmission capacity in accordance to growth of local demands. Also, favorable conditions for investors and an adequate tariff system are expected to stimulate the required development in the renewable energy sources, as to motivate both investors and end users to participate in sustainable energy production development.

In this study, particular attention is given to the renewable hydro- and wind energy technology based on the current structure of the Croatian energy sector. An overview of the currently used technology in offshore renewable energy is provided along with new concepts and technologies that could became an important part of the future Croatian energy system. Possible scenario for improving diversification of the energy sources and creating new jobs is outlined that is expected to strengthen Croatian economy and competitiveness on the global market.

2. Offshore renewable energy sources

One of the first and inventive attempts of offshore energy production dates back to 1970s, when concept and design of semisubmersible nuclear and gas plants were created [9,10]. The first offshore renewable energy power plant was built in 1991 in Denmark with almost 5 MW of the total installed power produced by eleven wind turbines, [11]. Since that time energy production demands have significantly increased leading to development of many different types of renewable offshore energy production units

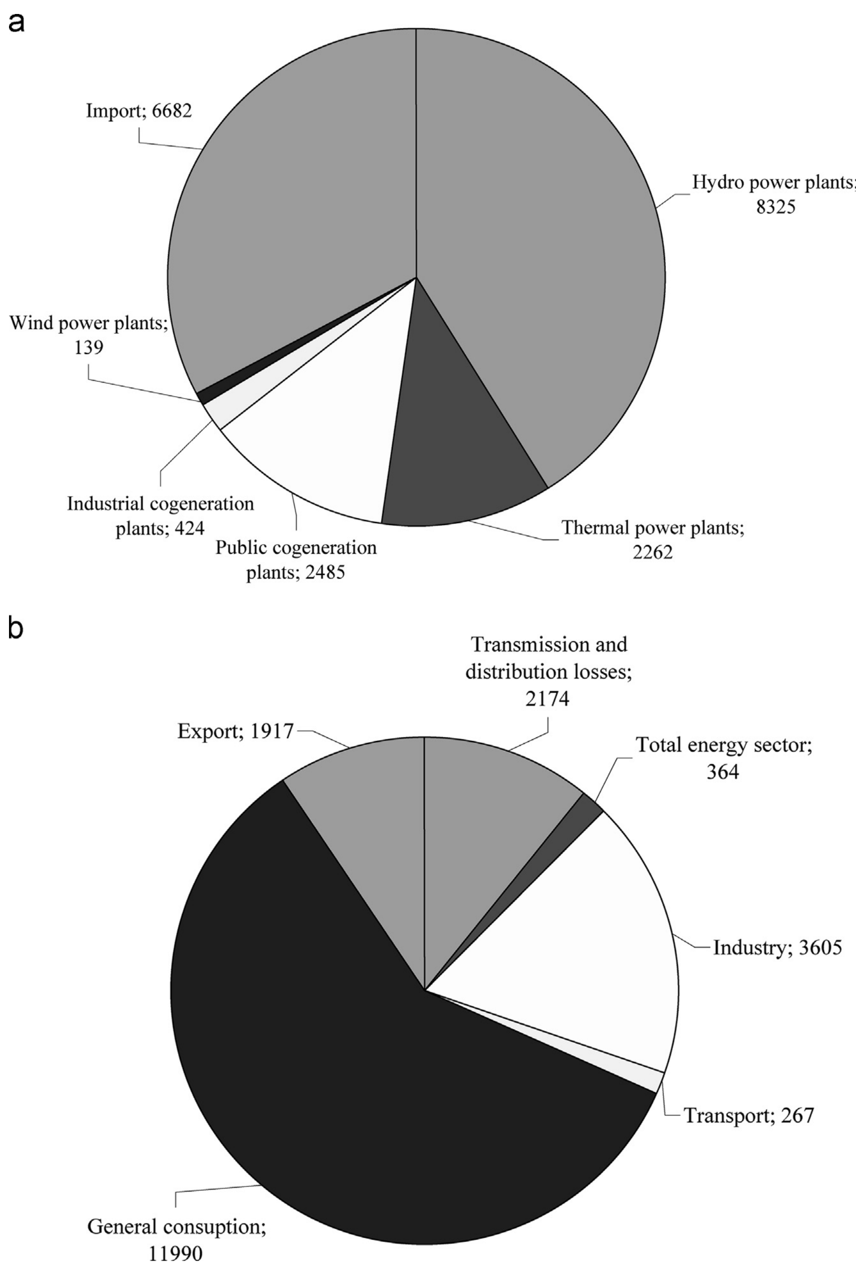

Fig. 1. (a) Total electrical energy production and (b) total energy consumption balance in Croatia for 2010 in GWh according to data available in [5].

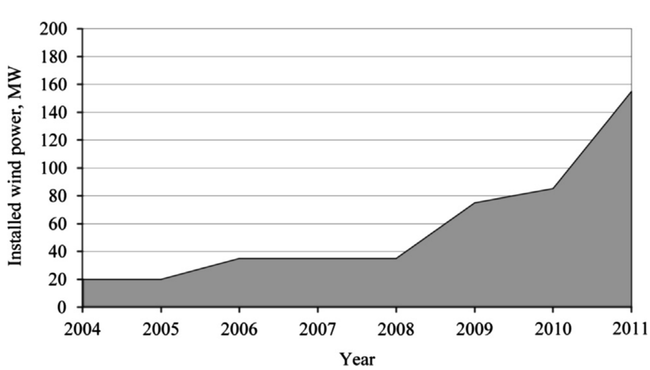

Fig. 2. Wind turbine installed capacities in Croatia for period 2004–2011, [6].

using wind, waves, current, thermal or chemical energy, [11,12], that can be considered as primemovers yielding electrical energy. The current intensive offshore energy production development took place mainly due to limited possibilities of wind power plant construction on land related to noise problems, visual pollution, available locations with desired environmental properties and commercial difficulties related to land renting or purchasing. It has been therefore driven by a strong ambition of exploiting huge and unused energy potentials that contributed particularly to the offshore primemovers attractiveness, [8,13].

In general, the offshore renewable energy has been predominantly produced by using aerokinetic and hydrokinetic devices. The former stands for devices placed above the sea surface driven by the atmospheric winds, while the latter placed beneath the sea surface are driven by the sea currents passing through the rotor disc, respectively. In that way rotational motion is induced and air or water kinetic energy is transformed into the electrical energy. One of the most prominent offshore aerokinetic energy extraction devices is horizontal axis wind turbine with fixed support structure (mainly monopile or gravity-base) as used in many countries, e.g. Sweden, United Kingdom, Belgium, Norway, Germany, China,

[14]. A common installed power is between 2 MW and 4 MW for water depths up to 25 m with a clear trend of increasing turbine size. For sea depths between 30 m and 40 m the jacket supporting structure is commonly applied. Main effort of the current research activities is focused on reducing production costs and developing new technologies that would make possible to install the wind power plants in the deep sea by using different types of floating support structures such as spar, tension leg or semisubmersible support, [12,14], as shown in Fig. 3.

Due to a nearly flat sea surface, offshore wind turbine has some favorable properties. In particular, nearly constant average wind velocity at the hub height along with weaker atmospheric turbulence, as compared to the wind developing over land, results with higher operating efficiency and lower structural fatigue of the wind turbine. Among other benefits, for offshore wind turbines it is possible to use longer wind turbine rotor blades for the same height of the wind turbine in comparison to the onshore wind turbines that yields more energy offshore than onshore. On the other hand, drawbacks are mainly related to demanding maintenance of offshore wind turbines, especially at high sea which requires development of special-purpose ship types. Hence, in order to design, manufacture, install and maintain such a complex offshore engineering structure operating in an aggressive meteorological and corrosive environment, highly specialized engineering knowledge and skills are required. More detailed overview of the present status, challenges and different technical and operational aspects related to offshore wind power plants can be found in [15,16]

A development of offshore wind turbines is accompanied by development of new and inventive hydrokinetic technology representing a set of devices driven by waves, tidal, river or ocean currents, [14,17,18]. At this moment, significant scientific, engineering and financial resources are focused onto development and commercialization of this challenging technology, especially with respect to tidal and current energy converters, [18,19]. Most prominent representative of emerging hydrokinetic technology is horizontal axis tidal turbine (HATT), Fig. 4, due to many favorable properties. Some important advantages of the HATT as compared to the wind turbines lie in the fact that the sea water density is about 830 times larger than the air density that enables the extraction of the same amount of energy across the considerably smaller rotor disc area making in such a way the HATT structure considerably smaller than the wind turbine that consequently

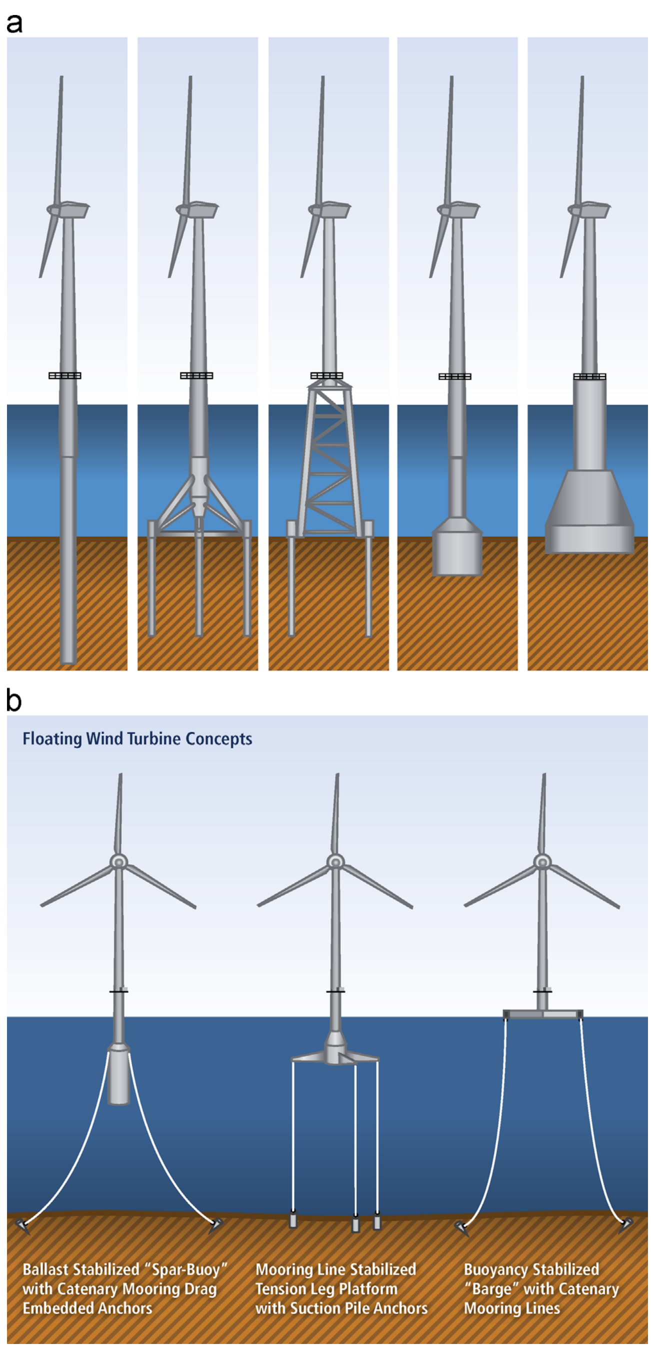

Fig. 3. Different types of fixed and floating offshore wind turbine supporting structure, [11].

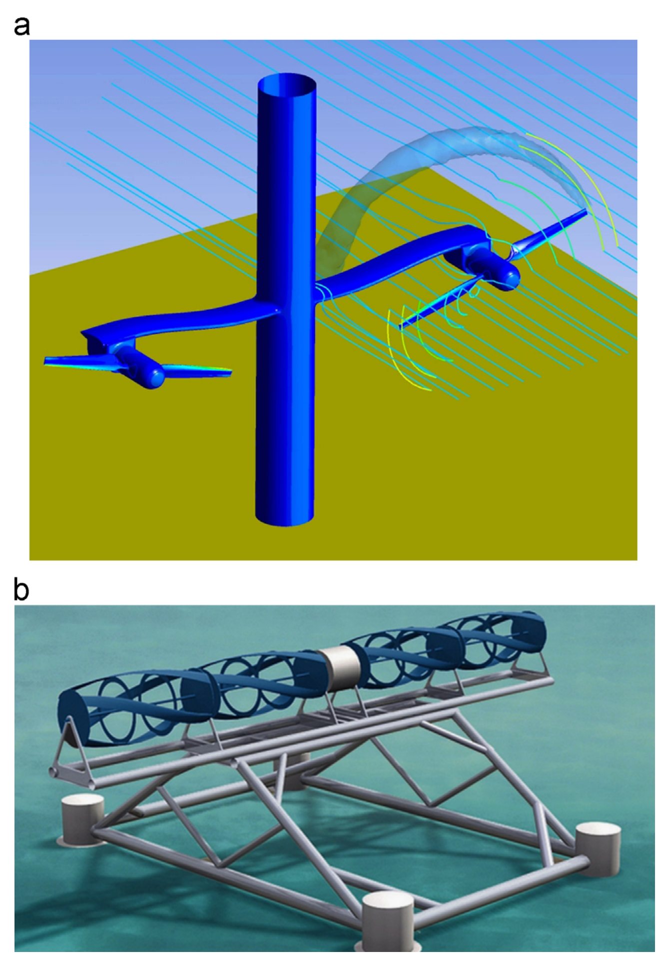

Fig. 4. An example of the horizontal axis tidal turbine in (a) axial, [20] and (b) cross-flow operational principle, [21].

enables easier, simpler and less expensive manufacturing, handling, transport, installation and maintenance. In addition, as the HATT device is placed below the sea surface, many environmental problems that apply to wind turbines above the sea do not exist for this case, such as for example visual pollution and obstacle for sea routes. Another important advantage in comparison to other renewable sources is high predictability of sea currents that simplifies their design and ensures favorable exploitation conditions. Some drawbacks are related to corrosive sea environment, sea fouling, non-uniform velocity profile of sea currents due to a friction between the sea flow and possibly rough sea bottom as well as possible underwater noise.

Current research activities with respect to the HATT devices are predominantly focused on possible application of knowledge and expertise gained through development of wind turbines above the sea surface as well as of marine propellers, since the development of the HATT devices is predominantly initiated through those two mature scientific fields. At this point, several HATT full-scale prototype installations have been commissioned, mainly in the United Kingdom, Ireland and Scotland with turbine installed power between 1 MW and 2 MW, usually in water depths up to 35 m, [14]. There are several supporting structure types, i.e. for tidal current devices the monopile, gravity or jacket substructure is commonly applied, while moored floating structure is suitable for deep-water applications in oceans. Both fixed and floating type turbines can also operate in improved hydrodynamic conditions by increased performance if ducted configuration is deployed using shrouded rotor. Moreover, except HATT axial flow operational principle, several tidal turbine operational schemes can be identified, i.e. vertical axis and horizontal axis cross-flow tidal turbines, as well as reciprocating turbines based on the mechanical oscillations induced by the vortex shedding or flutter fluid flow phenomena. In order to reduce investment, material, labor and maintenance costs, some of the design solutions have multiple turbines on a single supporting structure. Since tidal current flow is bidirectional, HATT needs to be designed as a reversible nacelle turbine, as HATT blades need to effectively use the kinetic energy of the flow from both directions. An advantage of cross-flow turbines in comparison to the axial-flow turbines is that they operate regardless of the flow direction. This feature is not present in case of ocean current application since they are unidirectional. In order to enhance the turbine output, the rotor shrouds can be applied for both axial and cross flow operational schemes, [12], where the controllable blade pitch ensures optimal operational conditions with respect to current speed and angle of attack.

Design of offshore wind and/or current power plants is a complex task involving different multidisciplinary stakeholders that need to be harmonized through subprocesses that are issued and elaborated along the design loop, while keeping the wind and/or tidal turbine output properties, as important income issue, in the focus of the design procedure. In order to deal with such a demanding task, the design process needs to be scheduled properly and carried out using some of the well developed design methods like linear programming, generic algorithms, differential evolution, [22,23], at different design levels during general, structural and hydrodynamic design. For general design purpose, it is important to distinct global and local variables of the offshore power plant. The former include distance between wind/current turbines and their layout within a farm, as well as geographical plant location. The latter include hub height/depth, rotor diameter, blade number and profile type as well as the supporting structure type of a single turbine. Global variables are expected to affect the overall power plant performance, since turbines placed within the plant generally have lower efficiency and larger fatigue in comparison to turbines at the upwind/upstream edge of the farm. Hence, this issue needs to be taken into a careful consideration in order to increase the energy yield and decrease structural loads.

Hence, design objectives and constraints with respect to an offshore renewable energy power plant need to be carefully considered. In particular, there are several key issues, i.e. (a) total investment reduction, (b) total power output increase, (c) reduction of fatigue in order to decrease maintenance costs, (d) best possible output electricity properties and (e) renewable energy source predictability and reliability. Some of the design constraints are related to geographical location properties (wind, wave and current microclimate, sea bottom profile), existing electrical power network, distance to the onshore substations, presence of other offshore objects (gas, oil, water and feces pipelines, cables), existing navigation routes, environmental and social impact, available commission and decommission technology solutions, fabrication and maintenance practice.

Design procedure based on a reliable algorithm strongly relies on accurate, physically sound and fast analysis models that need to be formulated in order to adequately include different structural, hydrodynamic, aerodynamic, hydroelastic, aeroelastic, production, commission and maintenance aspects in the design process along with their mutual interaction. A recent review of the analysis methods, [14], indicates many open questions, particularly with respect to floating wind turbines and tidal turbines. A particular focus is on structural dynamics due to aerodynamic and/or hydrodynamic loading, highly complex structural aeroelasticity and/or hydroelasticity issues.

3. The Adriatic Sea case study

In this section we outline a proposal for designing and manufacturing an offshore wind and sea current power plant in the Croatian part of the Adriatic Sea. This concept is developed based on knowledge and expertise currently available, [8,24,25]. First, wind and tidal current properties are investigated and the available data is summarized. Potential locations for offshore renewable energy power plants are suggested given the existing engineering infrastructure and sea traffic routes and a power output for a single wind and tidal current turbine is calculated.

3.1. Wind properties in the Croatian part of the Adriatic Sea

Offshore wind power in the Adriatic Sea is briefly considered in [2], where theoretical offshore wind potential within Croatian territorial waters of 61,067 km^2 is estimated to be about 150 TWh (540 TJ) of electricity. This estimate should be considered with caution, as the data body still needs to be further expanded and additionally validated. Therefore, current state-of-the art wind energy potential estimate for Croatia is based on the computational atmosphere model ALADIN, [26–28], of the Meteorological and Hydrological Service. The concept of the ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) was originally suggested by Météo-France in 1990 in order to develop a reliable high-resolution numerical tool for weather prediction. Ever since this model has been routinely used for the prediction of severe weather phenomena such as heavy precipitation, intensive convection and strong winds, as well as for research purposes. In this moment, approximately one hundred scientists from sixteen countries have been regularly contributing to further development of the ALADIN system, [29]. In this study, ALADIN has been used to calculate average wind speeds and power spectral density of velocity fluctuations at the altitude of 80 m above ground level. This prediction is made for one year period as average quantities within a 2 km $\times$ 2 km square, Fig. 5. Since energy potential of wind turbines is commonly determined based on the mean wind speed value at the hub height, results obtained at 80 m height are very useful, as this is one of the common

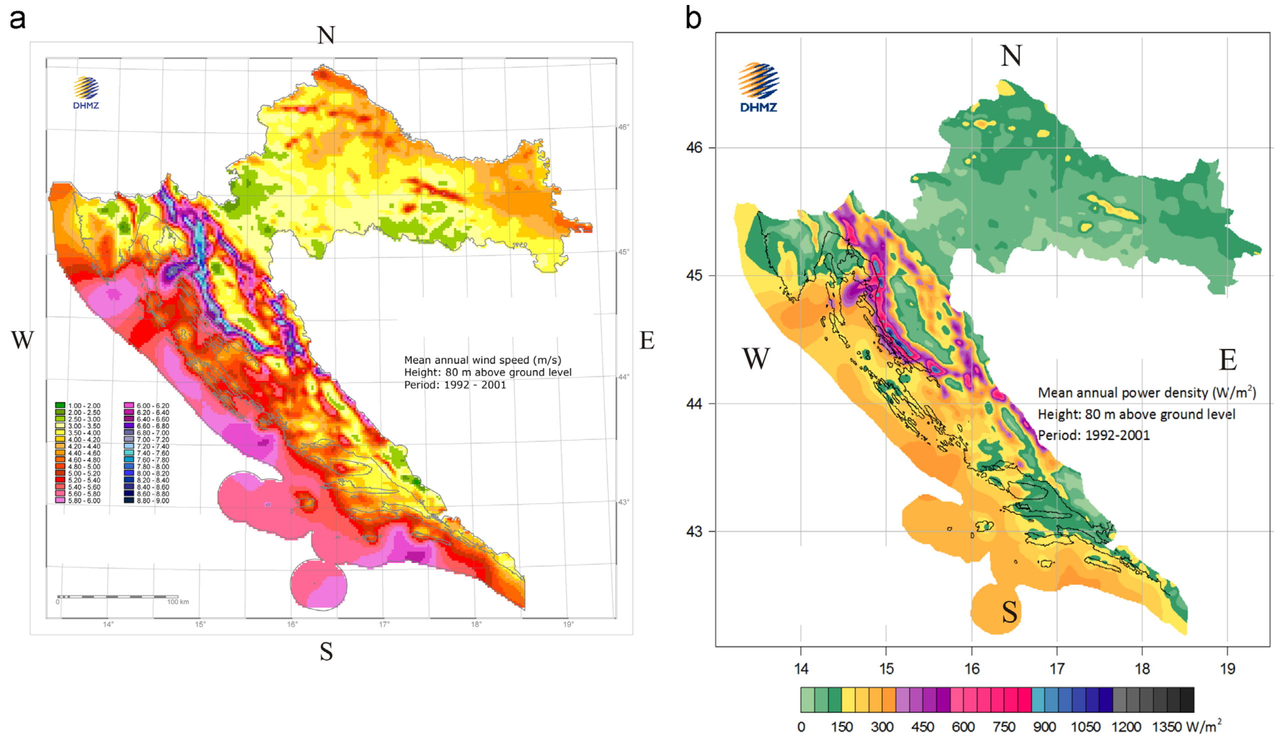

Fig. 5. (a) Mean annual wind speed at 80 m altitude, and (b) mean annual wind power density at 80 m altitude, [32]; x-axis denotes the longitudes, the y-axis denotes the latitudes.

heights of the currently designed offshore wind turbines. Mean wind speed at 80 m altitude achieves maximum value at open sea off the coastal cities of Pula and Šibenik, as well as close to the Lošinj and Mljet Islands, where average wind speed are approximately 6.5 m/s. As to the authors' best knowledge, the wind speed in the Croatian part of the Adriatic Sea has never been measured at open sea, this value needs further confirmation through field measurements and additional modeling. Moreover, it needs to be emphasized that current data does not encompass wind pulsations that can significantly influence the wind-turbine energy yield and structural loads. Therefore, the existing data can be used as a preliminary approximation, while a number of issues needs to be further addressed in the future, as for example atmospheric turbulence modeling, field measurements and wind-tunnel experiments [30,31].

An additional problem in the Croatian part of the Adriatic Sea represents the strong and gusty bora wind that develops at rather high and steep coastal mountains like Velebit and Biokovo, [31,33–36]. Due to its transient and gusty nature bora is expected to cause larger fatigue on offshore wind turbines in comparison to onshore wind turbines, as it previously proved to cause many problems in traffic, [37,38]. Bora's average wind velocity is rarely larger than 17 m/s [39], while the wind gusts can reach up to 70 m/s [40]. In addition, many Croatian islands can cause additional obstacles, as their presence decreases wind velocity and enhances atmospheric turbulence. Currently, a comprehensive research related to aerodynamics of offshore wind turbines in the vicinity of complex coastal terrains is underway within framework of the FP7-Marinet program, which is one of the largest research EU projects in the history with respect to renewable energy resources. The first results obtained within the FP7-Marinet project indicate a velocity decrease and stronger turbulence in the wind-turbine wake in presence of a coastal mountain [30]. This trend proved to be more exhibited for larger mountains and it weakens further downstream from the coast. Strong velocity gradients are observed at the hub height, as they increase with increasing the coastal mountain height. A research on wind characteristics within a wind farm placed off the mountainous coast is still underway and more results can be expected in the future.

3.2. Offshore wind power plant

For the purposes of developing an offshore wind farm, we identified three potential geographical locations in the Croatian part of the Adriatic Sea with respect to the key issues of an offshore renewable energy production: (a) wind properties, [32], (b) sea depth, [41], (c) existing navigation routes, [42], and (d) vicinity of the coastal electrical power network. When selecting those locations, no particular mathematical algorithm was used, as an approach was to eliminate clearly unsuitable locations and select those with an optimal (more favorable) combination of the parameters listed above. In particular, wind properties in the Croatian part of the Adriatic Sea are presented in Fig. 5 by means of mean annual wind speed and power density at 80 m altitude. Three potential locations can be identified with maximum mean annual wind speed and power density, i.e. the open sea off the city of Pula and the Lošinj Island, the open sea of the Mljet Island and the open sea off the city of Šibenik. The Adriatic Sea bathymetry maps, [41], were used in order to identify the most suitable location with respect to the sea depth. Three potential locations have the following maximum depths: 60 m, 90 m and 150 m, respectively, Table 1. Except that, navigation routes were considered according to [42], where three types of sailing routes can be identified. In particular, (a) the main longitudinal sailing route in the central Adriatic Sea connecting the Strait of Otranto and north Adriatic, (b) the main transversal sailing routes connecting cities at the eastern Adriatic coast (cities of Rijeka, Zadar, Split and Dubrovnik) with the cities at the western Adriatic coast (cities of Ravenna, Ancona, Pescara and Bari) and (c) the coastal sailing routes. Significant concentration of sea traffic is related to the main longitudinal sailing routes and especially at the intersection point with the transversal routes. This is particularly exhibited at

Table 1
Summary of important issues related to offshore wind power plant.

Location	Average wind speed, (m/s), [31]	Largest sea depth, (m), [41]	Substructure type	Sea routes, [42]	Electrical power network
Open sea off the city of Pula and the Lošinj Island	6.5	60	Fixed	Significant concentration of sea traffic	In vicinity (Pula or the Plomin power plant)
Open sea between the Žirje Island and the city of Primošten	6.5	90	Floating	Minor concentration of sea traffic	In vicinity (Šibenik)
Open sea off the Mljet Island	6.5	150	Floating	Minor concentration of sea traffic	/

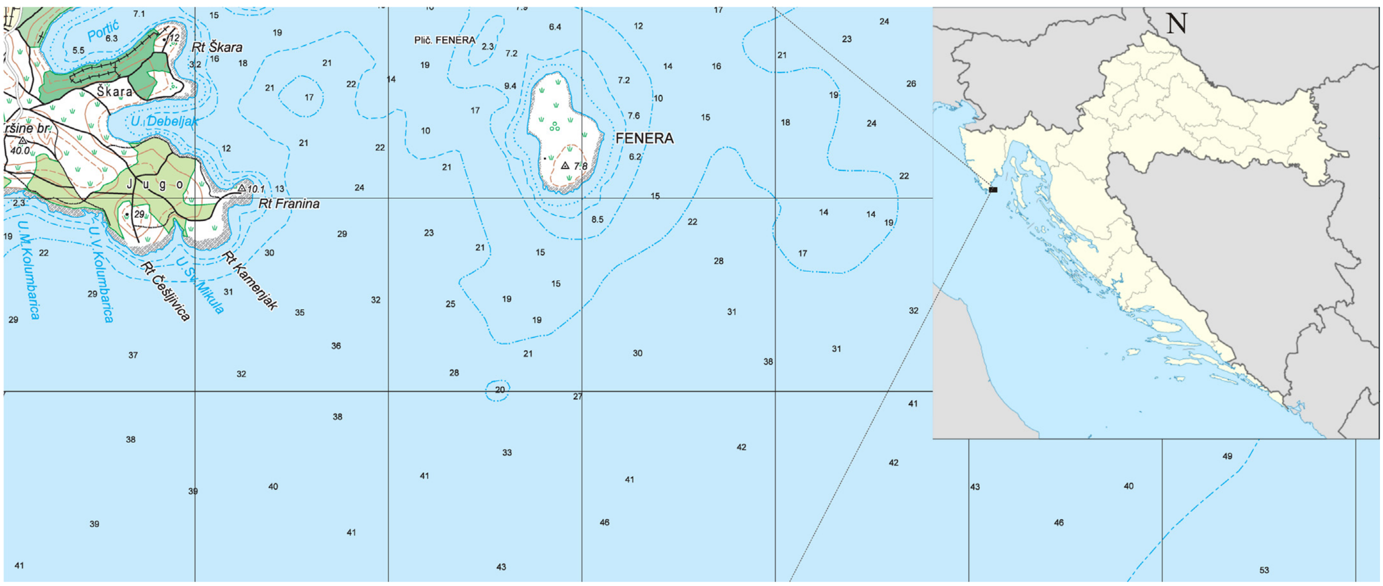

Fig. 6. Potential offshore wind power plant location (open sea off the city of Pula and the Lošinj Island), [41].

the Kvarner bay entrance since the city of Rijeka is the largest Croatian cargo port.

Taking into account all the above considerations, the open sea off the city of Pula and the Lošinj Island seems to be the most suitable due to the small sea depth (less than 60 m) and vicinity of the costal electrical power network (330 MW Plomin thermal power plant). However, possible difficulties could emerge due to considerable sea traffic as this is the entrance to the Kvarner Bay. Due to a larger sea depth, location in front of the Mljet Island is not convenient for offshore wind power plant, since the floating structure of wind turbines in such large sea depths significantly increases an overall investment. The optimal location with respect to sea routes is considered to be an open sea off the city of Šibenik, i.e. between the Žirje Island and the coastal city of Primošten. The drawback of this location is a significant sea depth around 90 m. According to the facts outlined throughout this section and based on the existing wind data for purposes of developing an offshore wind farm in the Croatian part of the Adriatic Sea we suggest an open sea off the city of Pula and the Lošinj Island, as presented in Fig. 6. All relevant issues with respect to the considered locations are summarized in Table 1.

Electrical energy produced by a single offshore wind turbine can be estimated using a well established expression, [43],

$$P = \tfrac{1}{2} C_P \rho v^3 \frac{D^2 \pi}{4}. \tag{1}$$

Assuming that at the hub height of 80 m the wind turbine has a diameter $D = 93.2$ m, [44], and taking into account that the approximate power coefficient is $C_P = 0.4$, air density, $\rho = 1.2\ \mathrm{kg/m^3}$, and average wind speed, $v = 6.5$ m/s, this yields the total amount of 3.94 GWh (14.184 GJ) electrical energy annually. Available average wind speed (6.5 m/s) is slightly larger than the lower operating wind speed limit (5 m/s) resulting with a relatively low level of produced energy. Therefore, further wind speed measurements and modeling are needed in order to allocate even more favorable locations. Based on the selected offshore location and the sea depth, the jacket-type substructure is selected for the wind turbines.

3.3. Tidal current properties in the Croatian part of the Adriatic Sea

A systematic and intensive multidisciplinary measurement in the north Adriatic Sea was carried out in the years 2002 and 2003 comprising of meteorological sampling, microstructure measurements and sea current measurements. An extensive meteorological and sea current data set was collected using Automatic Meteo-Oceanographic Station and Acoustic Doppler Current Profilers, [45,46], along with the study on west to east sea currents across the Adriatic Sea, [47].

For the purpose of this study and according to the literature available, several potential locations can be selected for consideration of an offshore renewable energy plant in the Croatian part of the Adriatic Sea. In particular, (a) open sea off the Dugi Otok Island with available monthly mean sea current velocity and direction with depths between 60 m and 70 m, [45], (b) open sea off the Mljet and Lastovo Islands, (c) open sea in line connecting the Gargano Peninsula in Italy and the Croatian coastal city of Split with available daily mean sea current velocity and direction with depths between 80 m and 140 m, [47], and (d) north Adriatic Sea, [46]. A comparison of the largest measured sea current velocities at the sea surface for specified locations is provided in Table 2.

It can be observed that the measured velocities are quite low in comparison to wind velocities above sea surface and they are approximately the same for different locations. Therefore, it needs to be taken into account that the sea current velocity is expected to be significantly larger for particular locations such as channels located between islands. Unfortunately, the measured data for such locations are currently not available, since the primarily purpose of previous measurements, [45–47], was to investigate the behavior of the Adriatic Sea as a closed system without detailed studying of particular topographies.

Table 2
Comparison of the largest measured sea current velocities at sea surface for different selected locations.

Location	Tidal current velocity, (m/s)
Open sea off the Dugi Otok Island, [45]	0.24
Open sea off the Mljet Island, [47]	0.20
Open sea off the Lastovo Island, [47]	0.20
Open sea off the Vis Island, [47]	0.22
North Adriatic Sea, [46]	0.20

3.4. Offshore tidal stream power plant

Based on the tidal current properties outlined for the Croatian part of the Adriatic Sea, we select several potential locations for the purposes of developing an offshore tidal stream power plants: (a) open sea off the Dugi Otok Island, (b) open sea off the Mljet and Lastovo Islands, (c) open sea off the Vis Island and (d) north Adriatic Sea. Similarly to considerations with respect to offshore wind turbines i.e. sea depth and vicinity of electrical power network, the north Adriatic Sea location presented in Fig. 7 seems to be the most favorable location with respect to the sea depth and costal electrical power network. On the other hand, possible difficulties related to sea traffic could emerge, although tidal turbines are not expected to significantly influence sea routes, since they are usually mounted on the sea bottom. All relevant issues with respect to potential offshore tidal stream power plant location are summarized in Table 3.

In the north Adriatic Sea, the hub distance from the sea bottom of 18 m can be assumed for two-bladed horizontal axis tidal current turbine operating in axial flow with diameter $D = 20$ m and reversible nacelle [48]. In order to improve turbine efficiency and decrease investment costs, a controllable blade pitch should be considered as well as installation of multiple turbines on single monopile supporting

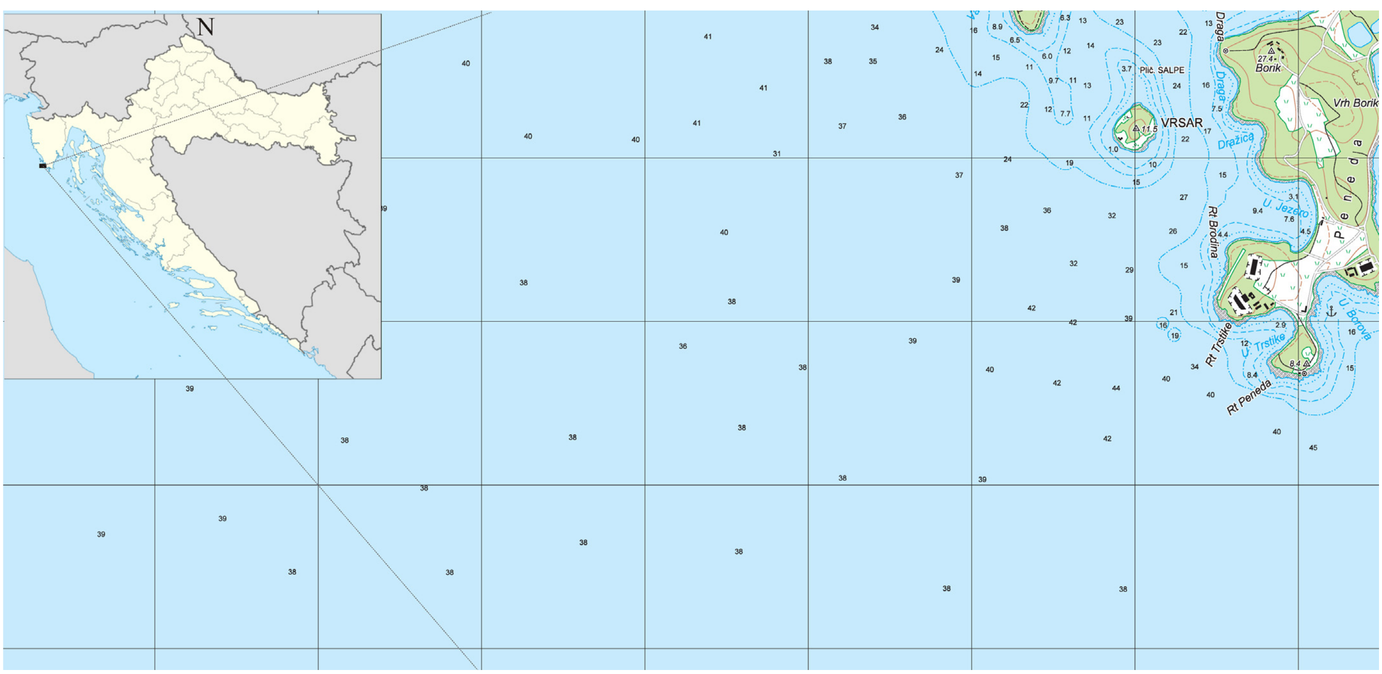

Fig. 7. Potential location for tidal current power plant location (north Adriatic Sea), [41].

Table 3
Summary of relevant issues with respect to the tidal sea current power plant.

Location	Tidal current speed, (m/s), [45–46]	Largest sea depth, (m), [41]	Substructure type	Sea routes, [42]	Electrical power network
Open sea off the Dugi Otok Island	0.24	70	Fixed	Minor concentration of sea traffic	/
Open sea off the Mljet Island	0.20	150	Floating	Minor concentration of sea traffic	/
Open sea off the Lastovo Island	0.20	140	Floating	Minor concentration of sea traffic	/
Open sea off the Vis Island	0.22	140	Floating	Significant concentration of sea traffic	/
North Adriatic Sea	0.20	50	Fixed	Significant concentration of sea traffic	In vicinity (Pula or the Plomin power plant)

Table 4
Comparison of thermal and potential offshore wind and current power plants with respect to installation, operation and maintenance cost [12,50].

Power plant	Installation, (USD/KW)	Operation and maintenance, (USD/KW)	Fuel, (USD/KW)	Total, (USD/KW)	Operating period, (years)
Thermal – coal	1800–2600	25–40	450–660	2270–3300	20–60
Offshore wind	2000–5000*	170–350	0	2170–5350	20–40
Sea current	4500–14300	100–140	0	4600–14440	20–40

* Only offshore turbines with fixed substructure.

structures. Taking into account the approximate power coefficient is $C_P = 0.4$, water density, $\rho = 1025\ \mathrm{kg/m^3}$, and average current speed, $v = 0.2\ \mathrm{m/s}$, this yields the total amount of 4.5 MWh (16.2 MJ) electrical energy annually produced by one device. An average sea current speed is quite low that consequently results with a relatively low level of produced energy. Therefore, further measurements and research are required in order to identify other potential locations with favorable sea current conditions, especially with respect to channels between the islands.

3.5. Discussion

The Croatian strategy is to install additional 1000 MW of wind turbine power until 2020 to maintain the renewable energy sources share as reported for the year 2010. Taking into account that the installed power of a suggested offshore wind turbine [44] is 2.5 MW, this yields a total number of 400 offshore wind turbines still needed in order to achieve this goal. Supposing that a single offshore wind power plant consists of 20 turbines, this gives 20 potential offshore wind power plants in total. Moreover, similar considerations can be applied to HATT devices in a case that a decision is made to apply them instead of wind turbines. In that case, taking into account that the installed power of a suggested HATT [48] is 2 MW, this gives a total number of 500 HATT devices in 25 power plants consisting of 20 HATT units. Furthermore, the abovementioned possibilities are in fact two extreme solutions with possibility of different power output share setups.

Suppose that a political decision of excluding significant air pollution energy production units, such as thermal power plants, is made. In that case the existing installed capacities would need to be replaced by some other sources, e.g. renewable energy sources. For example, let us consider the Plomin C coal thermal power plant that will have 500 MW of installed power until 2018. A total number of 200 offshore wind turbines with 2.5 MW of installed power would be necessary to replace it. Moreover, except from environmental point of view, such decision should be justified with respect to installation, fuel, operation and maintenance cost as well as from social and employment point of view. Installation costs are represented by the overnight capital costs, while operation and maintenance cost include fixed and variable costs such as land payments, routine maintenance, repairs, spare parts, waste disposal, emission fees or taxes, replacement power costs, etc.. All considered costs can vary significantly due to the state energy and environmental policies, business and regulatory context, world fossil fuel and commodity market, engineering service availability, labor expenses, local servicing infrastructure, turbine types, age, etc., [49]. A comparison of costs in terms of USD/KW and operating period related to thermal, offshore wind and current power plants is presented in Table 4 according to data available in [12,50]. It can be seen that the installation costs of the thermal power plant is lower than the investment needed to install offshore wind or current power plant, due to the fact that offshore renewable energy technology is characterized as still emerging and high-tech technology. That difference should become less pronounced as the know-how skills are gained and production technology is developed. In particular, the investment price of the thermal power plant is between 1800 and 2600 USD/KW. The installation cost with respect to the offshore wind turbines with fixed substructure is larger, as it ranges between 2000 and 5000 USD/KW. Quite large investment price between 4500 and 14,300 USD/KW is reported for the sea current turbines. Operation and maintenance costs are quite low in case of the thermal power plant (between 25 USD/KW and 40 USD/KW), as compared to the offshore wind and sea current turbines (170–350 USD/KW and 100–140 USD/KW, respectively), due to a demanding maintenance that involves supply units and special objects able to operate in high sea conditions. In addition, an expected lifetime is longer for thermal power plants in comparison to the offshore wind and sea current turbines that needs to be taken into account when considering an entire project. Social and employment considerations are presented in the following section along with the environmental impact of the considered offshore renewable energy in the Adriatic Sea.

Table 5
Comparison of potential offshore wind power plant and the Plomin C thermal power plant emission reported in [51] along with the investment price.

	Plomin C	Offshore wind power plant
SO_2 emission, t/year	1800	0
NO_X emission, t/year	2100	0
Particle emission, t/year	160	0
Investment, USD/KW	2200	3200–5000

4. Impact on environment, society and economy

Except fulfilling formal conditions according to the EU directives, Kyoto and post-Kyoto protocols, Croatia could gain some other important benefits from the development of an offshore renewable power plants, particularly in environmental and economical sense. Except being environmental friendly during the operation stage, renewable energy source technology could create new (including high-tech) jobs, as well as added value to the overall Croatian industry, especially shipbuilding.

In particular offshore wind and/or tidal power plant does not generate air pollution by the means of gas emissions (e.g. NO_X, SO_2, particles) and does not require other energy supply (like coal) in order to produce electricity, simplifying in such a way maintenance and reducing the operational costs. Comparison of a potential offshore wind power plant and the Plomin C thermal power plant with respect to emission and investment price is given in Table 5.

In addition to saving the environment, offshore wind and/or tidal current power plant in the Croatian part of the Adriatic Sea is expected to benefit the Croatian economy with respect to enhancing the production, installation and maintenance of such complex engineering structures. This refers to new challenges in knowledge and skills for planning, designing, execution of the whole project (general design, production planning, installation planning, logistics, engineering supervision, education of specialized staff, maintenance and safety

organization). This is expected to provide activity for relevant specialized offices, institutions, agencies, universities, research institutes and particularly for naval architects, civil engineers (foundations, soil mechanics), geophysicists (wind and wave microclimate), geologists (bathymetry), mechanical and electrical engineers (offshore substation, connection of the energy cable to the onshore substation). In favor of a scenario outlined in this study speaks a fact that Croatia does dispose of all the necessary institutions and experts, whereas there is potential to offer knowledge and expertise gained through activities related to an offshore renewable energy in the Adriatic Sea to other world markets as well.

It is important to notice that a social impact of the potential Plomin C thermal plant (currently under consideration) is significantly narrower in comparison to building an offshore power plant, as Plomin C relies to an expertise in civil and mechanical engineering only, while an offshore renewable energy power plant would engage much wider spectrum of professions. Therefore a larger initial investment in an offshore renewable energy power plant can be justified by a considerable and wide social benefit. In particular, while at this moment it is not completely possible to make an accurate estimation of the number of employees in the proposed offshore renewable energy power plant, it can be expected that all of the Plomin C employees (and more from other conventional power plants) would be able to get employment in this new facility. Moreover, in order to produce electricity in the thermal power plant Croatia needs to import coal that does not contribute to energy independence. Hence, a development of an offshore renewable energy power plant would significantly contribute to the independence of Croatia on imported coal that would additionally strengthen its geopolitical role.

Another key issue is reviving the Croatian shipbuilding industry, once one of the leading shipbuilding industries worldwide, with a potential to develop, design and produce specialized complex ships with high added value e.g.: heavy-lift vessel, wind-turbine installation unit, jack-up vessel, offshore supply vessel, cable laying ship, dredger and floating crane. At this moment, the Croatian shipbuilding industry is in the phase of production diversification considering a synergy between shipbuilding and energy industry, as both industries have numerous common characteristics. In particular, the final product dimensions in both industries are similar. They both deal mainly with steel and welding, forming, bending and casting processes, which enables to use the existing equipment in shipyards. Moreover, the Croatian shipyards have a necessary experience, [52,53], and production capacities (large workshops, cranes etc.), which can easily satisfy technology requirements with respect to onshore and particularly offshore wind turbine production. In particular, towers, nacelle heavy castings, substructures for fixed turbines and floating platforms for the floating structures. Another critical point is a strategic geographical location of the Croatian shipyards that makes them very attractive, since nowadays the largest cargo transport takes place by the sea.

The likely benefits of developing offshore renewable energy in the Adriatic Sea on the Croatian environment, society and economy are graphically presented in Fig. 8.

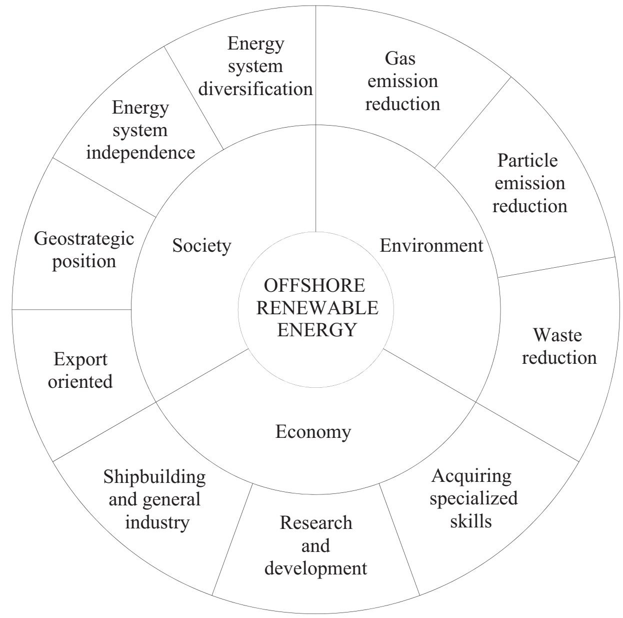

Fig. 8. Benefits of developing offshore renewable energy in the Adriatic Sea on the Croatian environment, society and economy.

5. Conclusion

As a full member of the European Union (EU), Croatia strongly committed to an intensive development in the renewable energy sector. In particular, each EU member state is supposed to reach the mandatory 20% share of renewable sources in the total energy consumption by the year 2020. With hydro power plants and onshore wind farms already being at their peak, at this point there is not a single offshore renewable energy power plant available in the Croatian part of the Adriatic Sea. Hence, in this study, we analyze a potential for development of an offshore renewable energy power plant in the Croatian part of the Adriatic Sea with likely implication on the environment and economy. A particular focus is on technology that would exploit the kinetic energy of wind and sea currents, whereas structural design issues, wind and tidal potential, sea depths, and sea traffic routes are analyzed in order to identify the potential locations for the proposed renewable energy concepts.

Based on the available data, an open sea location off the city of Pula and the Lošinj Island is suggested as a potential location for an offshore wind power plant with fixed supporting structure, while the north Adriatic Sea is suggested as a potential location for offshore tidal stream power plant. A relatively low energy production is expected in both cases, particularly for the tidal power plant, indicating a necessity of further measurements and modeling in order to indentify more favorable locations.

In addition to energy production, offshore renewable energy initiative would significantly influence Croatian environment, society and economy. In particular, their installation inevitably leads to gas and particle emission reduction, as well as diversification and independence of the Croatian energy system, since energy supplies such as coal or gas could be replaced by wind and/or sea water kinetic energy. In such a way many issues related to operational costs, maintenance and waste can be avoided. Also, Croatia would strengthen its geostrategic position since it could become export-oriented regional renewable energy production leader with foreign supply persistent energy system. Offshore renewable energy would benefit the Croatian shipbuilding industry as well, as this initiative would enhance acquiring specialized knowledge and skills required for development, manufacture, exploitation and maintenance of such complex engineering structures.

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